

Small-scale biomass CHP plants in Sweden and Finland

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ABSTRACT

Biomass continues to attract much interest as a renewable, low-CO₂, and increasingly cost competitive alternative to traditional fossil fuels for heat and/or electric power generation. At the same time, deregulation of electricity markets offer new opportunities for small-scale decentralized power plants (<20 MWe) in an area where traditional centralized technologies mostly dominate. These factors represent a strong driving force for the development of innovative small-scale combined heat and power (CHP) plants based on biofuels. This paper provides an overview of small-scale CHP with biomass as a fuel. A survey of existing plants in Sweden and Finland is presented, along with an overview of major energy conversion technologies under development. Information is provided related to energy taxation along with an outlook on future prospects.

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1. Introduction

Security of supply, sustainability, and environmental concerns are key issues that continue to strengthen the expanded implementation of biomass resources in the energy sector. In the European Union, it is proposed in the “Renewable Energy Road Map” setting a mandatory target of 20% for renewable energy’s share of energy consumption by 2020 and of 10% for biofuels [1]. In December 2008, this was enforced by adopting a resolution outlining the goals for 2020 in the energy sector at European level [2,3]. This resolution called The “Climate Action and Renewable Energy Package” aims at: achieving a reduction of EU’s overall emissions to at least 20% below 1990 levels; increasing the share of renewables in energy use to 20% by 2020 (from the current 8%) [2–5]; and improving energy efficiency by 20% compared to 2005. In order to comply with this target, Sweden needs to increase the energy coming from renewable energy from 39.8% in 2005 to 49% by 2020 [6]. Biomass resources are expected to play an important role in meeting this target.

Furthermore, the European Directive of Cogeneration (2004/8/CE) promotes cogeneration (i.e. combined heat and electric power production, or CHP) as a method to increase energy efficiency and reduce greenhouse gas (GHG) emissions in Europe. CHP lowers primary energy consumption by approximately one-third compared to the corresponding generation of heat and electric power in separate processes. Thus, the recovered heat in a fossil-fuelled CHP plant represents a reduction in carbon dioxide emission of about two-thirds and a two-fold increase in efficiency [7]. There is obviously a tremendous incentive to augment the share of CHP even further with biomass, a (nearly) CO₂ neutral fuel.

In 2000, approximately 11% of the electricity production [2] and 70% of the district heating is based on CHP plants in the 27 EU member-states [8,9]. However, in 2006, the EU’s Action Plan on “Energy Efficiency for 2007–2012” acknowledged that cogeneration accounted for only 13% of the EU electricity consumption in 2006 [10]. Nonetheless, cogeneration has been brought to the table once again in the “Climate Action And Renewable Energy Package” as a possible energy efficiency measure that can contribute significantly to the reduction in greenhouse gas emissions and reduction in the dependence on imported fuels.

In Sweden, the political goals to decrease the share of nuclear power production (with eventual phase-out) along with a moratorium on new large-scale hydropower constitute important factors for the development of CHP. In Finland, more than 70% of the district heat is already produced in CHP plants [11], but there is still potential to increase CHP production by converting district heating units for combined power and heat production. (Regarding nuclear power, Finland has gone the opposite route of Sweden and has commissioned the construction of a fifth reactor.) Primary biofuels in CHP plants include wood chips, sawdust, forest residues, bark and waste; biogas and landfill gas are also used to a lesser extent. Wood pellets are widely utilized in Sweden for heating purposes in both centralized and decentralized units. The current use of biomass (including peat) in Sweden is approximately 127 TWh/y for the primary energy supply [12]. It has been estimated that there is a potential of 248 TWh/y that could be used by 2020 [6]. In Finland, it has been estimated that about 117 TWh/y can be used by 2025 [13] compared to 92 TWh/y that were used in 2009 [14].

Traditional biomass-fired CHP plants have installed capacities ranging in the tens up to 100 MWe output, and this particular size is dictated by economic factors along with logistics (fuel harvesting and transport). One of the biggest challenges – and opportunities – linked to expanding biomass-based CHP lies in developing systems for even smaller scales. Energy market deregulation and other factors continue to make distributed generation (DG) a viable alternative to centralized power generation. These trends, com-

bined with the rising popularity of renewables, make small-scale, biomass-fired CHP a highly relevant alternative.

This article presents a state-of-the-art of biomass-based CHP technologies up to 20 MWe. Focus has been placed on applications in Sweden and Finland, two countries that are at the forefront of biomass-based CHP in Europe (owing in part to the strength of the forest industry). A survey of existing plants in these countries is presented, along with an overview of major energy conversion technologies under development. Finally, information is provided related to energy taxation, its impact in the energy system along with an outlook on future prospects.

2. Biofuels in Sweden

In Sweden, biofuels are used in substantial quantities in industrial and residential sectors. A breakdown of the different fuels used in each one of these two sectors during 2010 is shown in Fig. 1. Indeed, it is wood fuels (including black liquors) which is the renewable energy source most used in Sweden [12]. The current use of biomass (including peat) in Sweden is approximately 127 TWh/y (20%) [12]; [15] of the primary energy supply. Based on the current tendencies and the support given by electricity certificates together with the EU energy and climate policies it is expected that this share can increase to 248 TWh/y by 2020 [6].

Biofuels are mainly utilized in the forest industry, district heating plants, single-family houses, and to a lesser degree for electricity production. In the last category, it is estimated that about 21 TWh of electricity can be produced in biomass-based CHP plants [6,16] from the present 14.4 TWh/y [12]. In spite of being relatively widespread, biomass has still an important role to play in the energy system and particularly in the transport sector. Table 1 shows some examples of the potential in the energy sector for the different biomass products and their current use.

Table 1

Use of biofuels in Sweden and estimated potential for 2020 [6,18–23].

Biofuel type	Use in 2004 (TWh/y)	Estimated potential 2020 (TWh/y)
Forest residues	55	129
By-product wood from wood industries ^a	18	15.3
Tall oil	1.7	Unknown potential. Depends on the importing capacity and international tax rules.
Refuse wood	2	4.1
Agrobiomass	1 (0.2 ^b)	22 ^c
Salix	0.2	10–15
Red canary grass		1
Oat		0.001
Ethanol	1.9	6.5 TWh ^d
By-product from agriculture and food industries	0.025 ^e + 1.5 ^f + 0.1 ^g	
Straw		7
Peat	4	12 ^h
Landfill gas	0.40	0.5
Biogas	0.94	10
Pellets	3.57	
Briquettes	0.78	

^a Wood chips, sawdust, kutterspån and bark from sawmills.

^b 0.2 TWh came from energy forest.

^c Includes 9 TWh for the production of ethanol, biogas and RME (by LRF and Svebio).

^d Based on a production of 500,000 m³/y of ethanol from grains and 600,000 m³/y from forest residues (lignin) (LRF).

^e Oat shells.

^f Bio-oil.

^g Slaughterhouse waste.

^h If peat is classified in Sweden as biofuel [6].

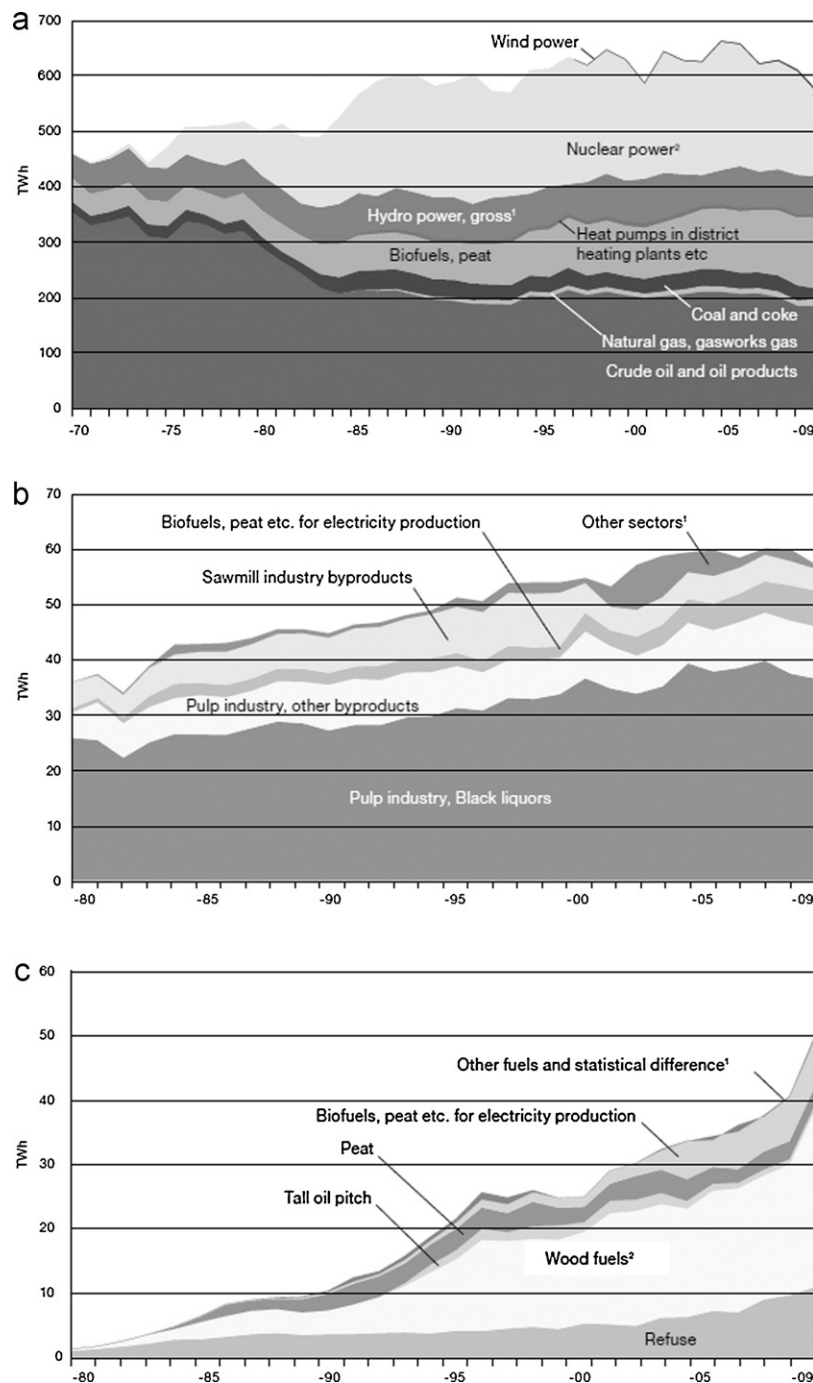


Fig. 1. Yearly use of biofuels in Sweden: (a) energy supply in Sweden by fuel type, (b) use of biofuels in industry, and (c) use of biofuels in district heating plants [12].

3. Biofuels in Finland

Biofuels have an important share in the total energy production in Finland. The well-developed pulp and paper industry and also the timber industry have helped to incorporate biofuels in the energy system by taking advantage of the residues. Fig. 2 shows the use of different energy sources in Finland since 1970.

The importance of biomass as energy source can be clearly seen in the energy consumption chart. For example, for 2009, the total energy consumption was about 370 TWh [24]. From this the utilization of biofuels corresponded to 15% and peat, 5% [24].

Regarding the use of biofuels in district heating and municipal cogeneration plants, renewable sources (wood fuels, wood residues, biogas and secondary heat from industry) contributed

with 18% of the 39 TWh produced in 2010 [25] and peat with 18% as it is shown in Fig. 3a. It can be seen from Fig. 3b that the use of renewable sources for district heating has increased rapidly in the past 12 years mainly because of the government's policy to favor this indigenous resource for the last 25 years including taxation measures (see Section 8.2). Furthermore, it is expected that bioenergy will contribute with 17 MWh/y in the district heating sector by 2025 [26].

In terms of electricity generation, wood fuels and black liquor contributed with 34% of the total electricity production in 2009 [27]. This corresponded to 23 TWh from wood-based fuels and 31 TWh from black liquor [27]. Also, peat contributed with 19 TWh.

For 2025, it has been estimated that the production of electricity from biofuels (without peat) will increase and the installed

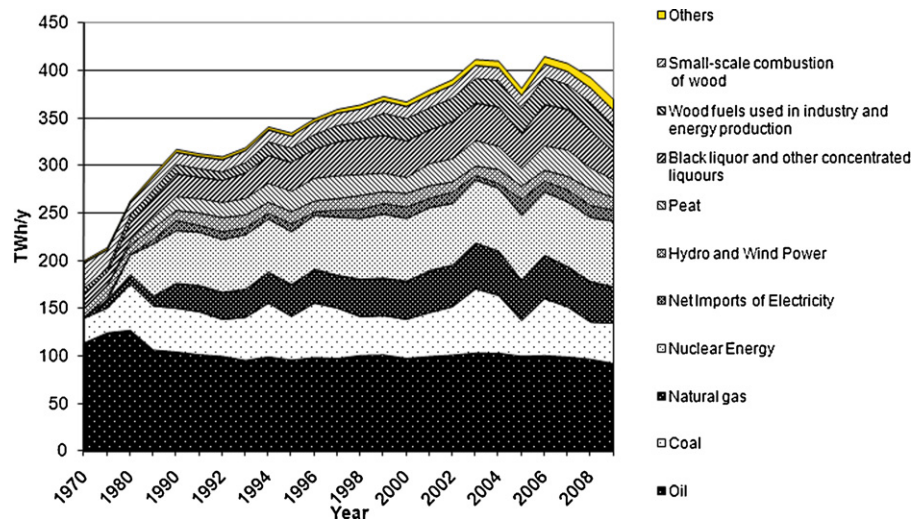


Fig. 2. Yearly energy source utilization in Finland 1970–2007 [24].

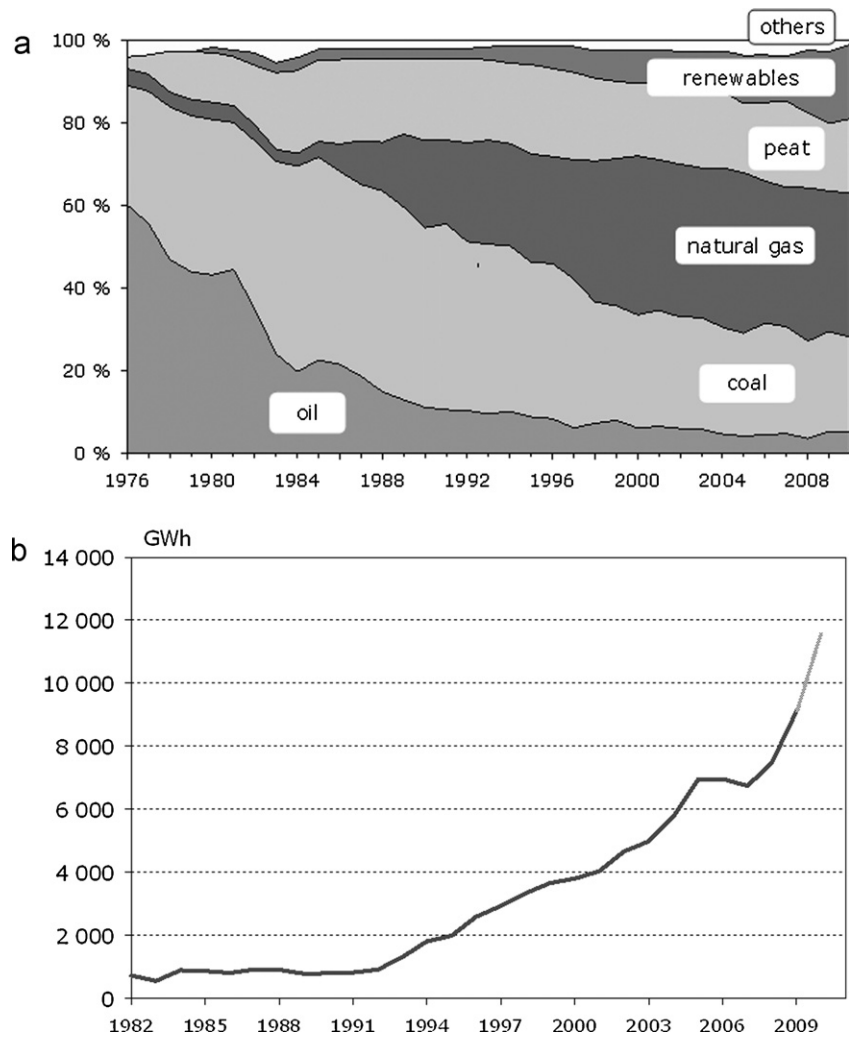


Fig. 3. (a) Fuels for district heat and cogeneration in Finland and (b) wood and wood residues in the production of district heat and cogeneration [25].

Table 2

Use of biofuels in Finland in 2007 [14,24,28,30] and Estimated Potential [13,28,29].

Biofuel type	Use during 2007 [TWh/y]	Estimated potential in 2025 [TWh/y]	Sustainable use of the resources [TWh/y]
Firewood	13.5	17	153 ^a 114 ^b
Forest chips	6.1	18	
By-product wood from wood industries	22	26	
Agrobiomass	0.25 ^c	1.4	13
Waste liquors from pulping	42.7	47	
Refuse	1.38	3	
Biogas	0.6 ^d	2.2	0.8
Liquid biofuels	0.39 ^c	2.5	
Peat	27.8		28

^a Harvested wood.^b Harvested residues.^c Data for 2005.^d Data for 2006.

capacity will increase from 3900 MWe (156 plants) in 2010 [12] to 4700 MWe by 2025 [28]. Also, calculations have shown that about 280 TWh/y can come from sustainable biomass compared to 90 TWh that were used in 2007. Table 2 shows more in detail the different types of biomass and their use in 2007, technical potential by 2025 and sustainable potential of the resource [29].

4. Small-scale heat and power plants in Sweden

Small-scale CHP plants have a relatively small market share in Sweden. The major reason for this is the large contribution of hydropower and nuclear power and historically low electricity prices. However, the price situation is changing rapidly as a result of deregulation and low-precipitation years. Political objectives leading to a decrease in the share of nuclear power production and a freeze on new large-scale hydropower production also drive the further development of combined heat and power production. CHP has approximately 15% share of the district heating production and 6% share of the electricity production in Sweden [31]. There is essentially no existing market for cogeneration in Sweden for installed capacities less than 1 MWe [32]. However, some CHP units in the range of 100–400 kWe were built in the early 1990s [33]. It was estimated that about 30–40 mini-cogeneration plants were in operation in Sweden during this period [32]. Table 3 shows the existing combined heat and power plants operating in 2001 at national level [34]. It is important to point out that these values are based on the plants that are registered in the NOx national registry and which have an electrical output over 25 GWh/y [35]. This is a general description of the situation in the small-scale CHP

sector. In terms of biofuel use, about 18 plants below 20 MWe used 0.6 TWh of biofuels for electricity and district heating production in 1999 [35]. Electricity produced in biomass-based CHP plants represented almost 9 TWh/y in 2002 [16]. Thus, it can be seen that small-scale CHP plants have a modest representation in the total electricity production from biomass.

For small-scale district heating units the situation is slightly different. About 26 plants presently are in operation with heat productions between 10 and 20 MWh, and 53 between 4 and 10 MWh and 119 below 4 MWh district heating production [35]. From this total of 198 district heating plants about 86 of them used biofuels in 1999 [35].

One of the main reasons for the limited representation of small-scale CHP plants in the energy sector is the small price difference between fuel and electricity [32]. Due to this important economic factor, some of the plants installed in the 1990s were taken out from operation. However, there is potential to replace small district heating units with CHP plants if the conditions change, i.e. the fuel/electricity price difference increases or the taxation system is modified. Also, there is a potential to connect single houses in small-scale district heating networks in Sweden [36]. The future potential for CHP in Sweden is judged to be in the order of 8 TWh/y by 2015 from an expected increase in installed capacity of 1250 MWe [37]. If this capacity increase is achieved, then CHP plants will contribute with 15% of the electricity production in Sweden in 2015. One of the most important points to highlight is that it is expected that approximately 60% of the CHP production will be based on biofuels [37]. From this amount, small-scale CHP might stand for 20% [32].

Table 3

Combined heat and power capacity in Sweden during 2001 [34].

Class (based on electricity production)	Data	Owner		Total
		Industrial sector	Energy sector	
<1000 kW	Total electrical capacity, kW	800	4340	5140
	no. of stations	1	5	6
1000–10,000 kW	Total electrical capacity, kW	101,960	104,930	206,890
	Number of stations	19	18	37
10,000–20,000 kW	Total electrical capacity, kW	115,105	204,725	319,830
	Number of stations	9	15	24
20,000–50,000 kW	Total electrical capacity, kW	523,000	521,900	1,044,900
	Number of stations	15	16	31
50,000–100,000 kW	Total electrical capacity, kW	226,540	461,000	687,540
	Number of stations	3	7	10
100,000–150,000 kW	Total electrical capacity, kW		353,500	353,500
	Number of stations	3	3	
>150,000 kW	Total electrical capacity, kW		1,122,700	1,122,700
	Number of stations	5	5	
Sum total, kW		967,405	2,773,095	3,740,500
Sum total, number of stations		47	69	116

Table 4

Example of Biomass CHP plants from 1 to 20 MWe built in Sweden between 1990 and 2009 [40–44].

Power plant	Power output (MWe)	Heat output (MW)	Fuel input (MW)	η_{el} (%)	η_t (%)	α	Steam values (bar/°C/kg s ⁻¹)	Fuel	Technology	Start up year
Bäckelund	7	23	35	20	85–90	0.3	40/400	Wood chips/municipal waste	Grate	2009
Strängnäs	8.9	36.5				0.24		Wood chips, wood residues	Grate	2009
Halmstad	3.2	19.3				0.17		Wood residues	Biograte	2008
Arsta	6.3	25 + 5 ^d				0.25	70/485/–	Wood chips	Grate	2007
Motala	3.7	17.5	20	18.5	95	0.21	51/485/–	Wood chips, bark, sawdust	Biograte	2007
Älvsbyn	3	10 + 3 ^d	13	23	100	0.23	60/450/–		Grate	
Lextorp (Trollhättan)	3.7	17.4	20	18.5	87	0.21	51/485/–	Wood chips, bark, sawdust	Biograte	2006
Tranås ^a	1.6	8.3 + 2.7 ^d	11.5	14.5	104	0.19	16/345/3.4	Sawdust, bark	Biograte	2002
Härnösand	11.7	26 + 7 ^d	42	28	106	0.45–0.49	92/510/14	Forest residues, bark, sawdust, peat	BFB	2002
Lycksele	14	28	50	32	84	0.51	88/520/17.5	Wood	CFB	2001
Sala	10	22	36	28	89	0.45	80/480/12.6	Wood	BFB	2000
Lomma	3.5	14	18.3	19	93	0.25	60/510/5.7	Wood, paper residues	FB	1995
Kristianstad	13.5	35	55.5	24	87	0.39	65/510/17.5	Wood	CFB	1994
Värnamo ^c	5.5	9	18.5	30	76	0.67	40/455/–	Wood	IGCC	1994
Falun	8	22 + 8 ^d	35	23	109	0.36	63/490/10.2	Bark, wood residues, wood chips	BFB	1993
Hudiksvall	13	36	60	22	82	0.36	67/475/18	Wood, peat	Grate	1992
Karlstad	20	55 + 20 ^d	88	20	108	0.36	66.7/500/29	Wood	CFB	1992
Malå	3	10	16.3	18	85	0.30	41/480/4.4	Wood	BFB	1991
Nässjö	9	20 + 6 ^d	36	25	100	0.45	85/490/12	Wood	CFB	1990
Hallsberg ^b	2.05	9	14.1	14	80	0.23	65/500/4	Wood	Multibed	1987

^a Started on 2002.^b Constructed in 1987, currently out of operation.^c Currently out of operation.^d This heat addition indicates heat produced by flue gas condensing. The heat coming from flue gas condensing is considered when calculating total efficiency but not when calculating power to heat ratio.

Currently there are several CHP plants in the range from 1 to 20 MWe using biomass in Sweden, as shown in Table 4. Two CHP plants have an output on the low end of the size range, around 2 MWe. The Tranås CHP plant uses a special grate technology designed for biomass combustion. The Hallsberg CHP plant is out of operation since 2000 because of economic reasons. The boiler technology in Hallsberg is based on a fluidized multi-bed technology, which allows the co-firing of different fuels. In both power plants the electrical efficiency is about 14%. In the size range of 3 MWe, CHP plants can be found in Malå and Lomma. Both are based on fluidized bed technology. The total efficiencies of these plants are over 85%, but the electrical efficiencies remain slightly under 20%.

The integrated gasification combined cycle process has been demonstrated in Värnamo with a 5.5 MWe CHP plant. The plant was based on a pressurized biomass gasifier and on combustion of the cleaned gasification gas in a gas turbine. The flue gases of the gas turbine were utilized in a heat recovery boiler which produced steam for a steam turbine. The plant has a high electrical efficiency and a high power to heat ratio, but the total efficiency of the plant

is somewhat low. The plant was taken out of operation in the 1990s due to economical reasons. However efforts are currently ongoing to modify this unit to produce transportation fuels from synthesis gas within the framework CHRISGAS, a multinational European demonstration project [38,39].

The CHP plants in the size range from 8 to 20 MWe in Sweden rely on the conventional Rankine cycle. Five of the plants listed in Table 4 also have flue gas condensing to increase the heat production. Because of this extra heat production, the total efficiencies of these plants can rise to over 100% (based on fuel lower heating value). Power-to-heat ratios (α) have been calculated without flue gas condensation to be able to compare the power plants in Sweden and Finland. The difference in the taxation system between these 2 countries has made flue gas condensation primarily feasible in Sweden. Their values range from 0.36 to 0.45. The electrical efficiencies are between 20% and 32%.

As stated previously, it is estimated that there are only about 30–40 CHP plants with less than 1 MWe power output in Sweden (most of them research or demonstration plants). Some of the plants under 1 MWe are based on gas engine technology

Table 5

CHP demonstration plants in Sweden (<1 MWe) [40].

Power plant	Power output (MWe)	Heat output (MW)	Fuel input (MW)	η_{el} (%)	η_t (%)	α	Fuel	Technology
Papyrus, Mölndal	0.033	0.065	0.13	25	75	0.5	Natural gas	Microturbine
Varberg	0.2	0.18	0.53	38	70	1.1	Natural gas	PAFC
Lund Tekniska Högskolan	0.6	1.03	1.09	55	94	0.6	Natural gas	EvGT
Stockholm	0.29	0.82	0.97	30	85	0.4	LPG	Gas engine
	0.23	0.68	0.74	31	91	0.3		
Kävlinge	0.1	0.3	0.50	20	80	0.3	Natural gas	Microturbine
Älvkarleby	0.0008						Wood pellets	Stirling engine

Table 6

Natural gas and biogas CHP plants in Sweden (<1 MWe) [40].

Power plant	Power output (MWe)	Heat output (MW)	Fuel input (MW)	η_{el} (%)	η_t (%)	α	Fuel	Technology
Varberg	0.29	0.45	0.83	35	90	0.64	Natural gas	Gas engine
Jönköping	0.99	1.3	2.61	38	88	0.76	Natural gas	Gas engine
Eskilstuna	0.65	1.17	1.09	55	94	0.56	Natural gas	Gas engine
Laholm	0.45	0.65	1.2	38	85–90	0.69	Natural gas	Gas engine

(see Table 6) while some are demonstration plants use non-commercialized technologies (see Table 5). These plants can be divided in three categories [32]:

- CHP plants using biogas or landfill gas in a gas engine. The main driving force of these plants is cheap fuel. These plants provide heat to the district heating network and electricity to the grid to maximize the economic benefits.
- CHP plants using natural gas that produce electricity and heat for industrial or residential buildings (Table 6).
- Demonstration plants to gain experience or test new technologies (Table 5).

5. Small-scale heat and power plants in Finland

In Finland, CHP plants cover a much higher proportion of power and heat production than in Sweden. In the year 2008 about 74% of the district heating and 31% of the electricity in Finland was produced with CHP plants [40]. Although there is already a high share of CHP plants in Finland and many large-scale power plants have been converted to CHP plants, it is still possible to increase the amount of CHP via small-scale units. There are many regional small-scale district heating plants that could be converted to combined power and heat production. The potential to increase CHP production in Finland has been estimated to be around 5–8 TWh per year.

In Finland many CHP plants sized under 20 MWe have been built during the last ten years, as presented in Table 7. In the size range under 1 MWe, there have been two technologies used in Finnish CHP plants. At Tervola, the CHP plant produces 0.47 MWe with a new process where the fuel is gasified with a special gasifier in a combined counterflow/parallel flow process. The dirtier product gas from the counter flow process is burned with a separate gas boiler, and the cleaner product gas from forward flow is cleaned and burned in a gas engine. In this process, both the electric effi-

ciency and the power to heat ratio are relatively high. There have been some problems with the gas cleaning before the gas engine, which delayed the start up of continuous electricity production. At Kiuruvesi and Karstula there are around 1 MWe CHP plants where a rotating grate boiler is used for steam production. The steam is led into a steam turbine for electricity production. The electrical efficiency of these plants is around 10%, but the total efficiency is 85%.

The Finnish CHP plants in the size range from 5 to 20 MWe still rely on the conventional Rankine cycle. The boiler type used in this size range is fluidized bed. The difference of these plants with the corresponding plants in Sweden is that flue gas condensing is not employed. The electrical efficiencies of the CHP plants in the range from 5 to 20 MWe vary between 22% and 25%. The only exception is the Iisalmi power plant, where the electrical efficiency is 31%. Also the power to heat ratio of the Iisalmi CHP plant is higher than in other CHP plants, where the ratio is between 0.20 and 0.40. Total efficiencies of the CHP plants are all quite similar varying between 88% and 93%. Many of these biomass CHP plants relying on Rankine cycles use also peat with wood fuels; for example, in Iisalmi power plant the peat proportion is 70% of the heat output. In many cases, though, it is possible to increase the proportion of wood fuels in the boiler. In Iisalmi the wood proportion could be increased from 30% to 70% without any equipment modifications.

In 2000, the production capacity of CHP plants was 4100 MW electricity and 5700 MW heat [40]. It has been estimated that the potential of CHP plants using biofuel, natural gas and peat is about 600 MWe and 1000 MWh with 6000 h of annual peak load time based on district heat energy consumption [40]. For 2000 h annual peak load the potential has been estimated to be 3700 MW electricity and 5000 MW heat [40]. Of the potential CHP plants 91% would be in the size below 20 MWh with the 6000 h peak load. With 2000 h peak load 74% of the potential would be under 20 MWh.

Table 7

Biomass CHP plants <20 MWe built between 1990 and 2009 in Finland [40,45–47].

Power plant	Power output (MWe)	Heat output (MW)	Fuel input (MW)	η_{el} (%)	η_t (%)	α	Steam values ($^{\circ}\text{C}/\text{bar}/\text{kg s}^{-1}$)	Fuel	Technology	Start up year
Björknäs	3.6	17.6	17	21	104	0.20	–	Wood chips, wood residues	Grate	Autm. 2009
Kokemäki	1.8	4.3	7.2	25	60	0.42	–	Wood chips, saw dust, bark, peat and various REF fractions	Gasification and gas engine	2006
Vilppula	2.9	13.5	16.8 (19.3)	17	80	0.21	450/50/5.83	Bark and sawdust	Biograte	2004
Renko	1.3	8	9.8	13	81	0.16	450/23/–	Bark and sawdust	Biograte	2004
Iisalmi	14.7	30	48.0	31	93	0.49	93/515/17.5	Peat, wood, REF	BFB	2002
Tervola	0.47	1.13	2.0	24	82	0.42	–/–/–	Wood residues	Gasification and gas engine	2002
Karstula	1	10	12.9	8	85	0.10	24/350/–	Bark, sawdust	Grate	2000
Kiuruvesi	0.9	6	8.1	11	85	0.15	25/350/2.8	Bark, sawdust, wood chips	Grate	1999
Forssa	17.2	48	71.7	24	91	0.36	62/510/22.8	Wood, REF	BFB	1996
Lieksa	8	22	33.9	24	89	0.36	61/510/8	Peat, wood	BFB	1994
Kuusamo	6.1	17.6	27.6	22	86	0.35	61/510/8	Peat, wood chips, sawdust	BFB	1993
Kankaanpää	6	17	26.0	23	89	0.35	60/510/7.9	Peat, wood	BFB	1992
Kuhmo	4.8	12.9	20.1	24	88	0.37	81/490/–	Wood residues	CFB	1992
Kokkola	20	50	78.7	25	89	0.40	80/482/27	Peat, wood	BFB	2002

Table 8a

Cogeneration plants in Sweden and Finland according to the technology used [17,50].

Cogeneration Plants	Sweden ^a	Finland ^b
Number of combined heat and power plants	108 ^c	82
Total electricity capacity (MW)	4325	4300
Total heat capacity (MW)	12,051	5970
Steam turbines		
Electricity capacity (MW)	3674 ^d + 291 ^e	3860
Heat capacity (MW)	10,188 ^d + 949 ^e	5370
Gas turbines		
Electricity Capacity (MW)	340 ^f	340
Heat capacity (MW)	518 ^f	480
Diesel and gas engines		
Electricity capacity (MW)	20 ^d	100
Heat capacity (MW)	396 ^d	120

^a For the year 2008.^b For the year 2001.^c Including conventional thermal plants.^d Completely CHP units (efficiency $\geq 75\%$).^e Units with a non-CHP component (efficiency $< 75\%$).^f Includes combined cycle and gas turbine with heat recovery.

6. Comparison between Sweden and Finland

Sweden and Finland have certain differences in their energy systems, particularly in thermal power generation. In Finland, district heating CHP plants are mainly fuelled with coal, oil and natural gas (see Fig. 3b). Fossil fuels contributed with 65% of the fuel consumption in district heating and CHP plants [11]. In Sweden, on the contrary, most of the fuels used for district heating and cogeneration are biomass-based (Fig. 1c). This certainly has an effect on the heat and power technologies used particularly as natural gas is an easier fuel to use specially in combined heat and power plants with a power output of less than 1 MW. Table 8a shows a comparison of the installed thermal capacity according to the technology used.

There is also a difference in both countries considering that district heating has more coverage in Finland than in Sweden. In Finland about 50% of the heat requirements are covered by district heating and in densely populated areas can reach more than 90% [48]. In 2008, district heating production reached 32 TWh [25]. The district heating system is mainly supported by CHP plants which

depending on the climate conditions cover between 75% and 80% of the demand [48]. District heating in Sweden does not have the same coverage for the residential and commercial sectors. In 2008, about 82% of the apartment blocks, 68% of the commercial premises and only 12% of detach houses used district heating [12]. In 2009, the total production of district heating was 60 TWh [12] of which 44% were produced in CHP plants [49].

In terms of biomass potential, Sweden has about 122 TWh/y that could be used for energy purposes by 2020. In contrast, the Finnish biomass potential has been estimated to be 117 TWh/y by 2025 which means an increase of 27 TWh/y from the current supply. This means that the possibility to increase the use of biomass fuels for CHP plants in order to contribute with the reduction in emissions is very limited. In contrast with Sweden, Finland has increased its emissions in the past years and has exceeded the limit established in Kyoto [51]. In 2008, emissions were kept at the level of 1990 and met the requirements of the Kyoto protocol mainly due to a reduction in the country's energy consumption. In the current situation and with the new European directive for 2020 it is imperative that Finland uses as much as possible its renewable resources to cover the energy demands.

Sweden it is in a better situation in relation to the Kyoto protocol with emissions lower than the limit established. However, there are other incentives playing an important role in the implementation of biomass cogeneration plant namely electricity certificates and the new European resolution "Climate Action and Renewable Energy Package".

7. Technology review for small-scale CHP plants

A review of the current and future technologies for small-scale CHP production has been performed by considering fuel availability, technology development status, economy, possible applications and environmental aspects. For each technology the limitations, possibilities, advantages and disadvantages from the Nordic perspective are discussed. A summary of different technologies is presented in Table 8b. Nowadays, the technologies that are commercially available (or close to that point) are conventional Rankine cycle, gas turbine with heat recovery steam generator, steam engines, microturbines, internal combustion engines, Stir-

Table 8b

Summary of different small-scale energy conversion technologies [35,56–58,60,64,65,67–71,74–78,80–84].

Technology	Power output MWe	Electrical eff. %	Total eff. %	Investment cost [EUR/kWe]	Possible biofuels
Commercialized					
Conventional Rankine cycle	0.5–100	20–30	85–93	~1500	Most of solid, liquid or gaseous biofuels
Steam engines	0.02–5	6–20	85–95	~1500	Most of solid, liquid or gaseous biofuels
Gas turbines with HRSG	0.1–200	24–40	80–85	840–1200	Gaseous biofuels, methanol, ethyl alcohol, RME
Microturbines	0.025–0.5	11–33	70–90	800–1700	Possible to use methanol, ethanol, colza oil, pyrolysis oil, biogas
Otto engines	0.002–2	25–40	80–90	800–1300	Ethanol, methanol, gaseous biofuel
Diesel engines	0.05–50	40–45	85–90	1200–1800	Pyrolysis oil, pine tree oil, colza oil, RME, gaseous biofuels
Stirling engines	0.001–0.075	20–40	80–90	~3500	Most of solid, liquid or gaseous biofuels
Fuel cells: PAFC	0.2–1	40–45	~90	~3000	Hydrogen, methanol
SOFC	0.005–10	45–60	~80	1000–1500	Hydrogen, hydrogen + CO
MCFC	0.2–5	50–60			Hydrogen
PEFC	0.001–0.25	35–40		~3000	Methanol, hydrogen
Under development					
Organic Rankine cycle	0.002–10	10–30	~85	~4500	Most of solid, liquid or gaseous biofuels and waste heat
Air bottoming cycle	0.1–250	30–44	~80		Gaseous biofuels, methanol, ethyl alcohol, RME
Evaporative gas turbine	5–25	~55	~94	1280	Gaseous biofuels, methanol, ethyl alcohol, RME
Externally fired gas turbine	0.007–1	31–38	86–106	2800–3900	Most of solid, liquid or gaseous biofuels
Pulverized wood-fired gas turbine	3–5	35–45			Sawdust
Powdered fuel combustion engine	0.01	35–40			Sawdust
Thermoionic converters		5–25			Most of solid, liquid or gaseous biofuels
Thermophotovoltaics		~10			Wood

SOFC in combination with a microturbine.

ling engines and fuel cells. Technologies that are still under research or near to a commercial breakthrough are, e.g. organic Rankine cycle, air bottoming cycle, evaporative gas turbine, externally fired gas turbine, pulverized wood-fired gas turbine, powdered fuelled combustion engine and thermoionic converters.

The nature of the biofuel type (i.e. gaseous or solid, purity, heating value, etc.) obviously has a significant influence on the particular CHP technology employed. In some cases it is necessary to add extensive conversion steps to further refine the biomass feedstock to a usable fuel. Such technologies include gasification, pyrolysis, distillation, anaerobic digestion, and others. A discussion of these aspects is beyond the scope of this article; focus is rather placed on the CHP systems themselves. Further information on thermochemical and biological conversion of biomass can be found in McKendry [52–54].

A summary table (Table 8a) is presented at the end of this section with the most relevant characteristics of each technology (i.e. power output range, efficiency, investment cost and fuels that can be used). Table 8a contains a summary of the technologies for power generation used in Sweden and Finland.

7.1. Commercially available technologies

7.1.1. Conventional Rankine cycle

Most of the power plants using solid biomass are based on a conventional Rankine cycle. Usually these plants use a fluidized bed boiler together with a steam turbine. In Sweden and Finland, the Rankine cycle is most commonly used in power plants producing above 3 MWe. The total efficiency of the Rankine cycle is very high reaching above 85%, especially when the primary product of the plant is heat. The most common fuels used in Swedish and Finnish biomass plants are wood chips, bark, sawdust, forest residues and pellets, but peat may also be used in a mixture with wooden fuels.

The steam pressure of a conventional Rankine cycle can range from few bars to 100 bar for cogeneration applications, and the temperature may range from few degrees of superheat, to around 540 °C [55]. It is also possible to have additional low-temperature heat production by using flue gas condensation, particularly if the fuel has high moisture content. More research is needed to avoid corrosion in the superheaters of the boiler and to increase the electrical efficiency by using advanced steam conditions [56]. Advanced steam conditions reduce the volume flow in the turbine and would allow for higher electrical efficiencies [56]. It is expected that steam conditions of 100 bar/600 °C will be possible in the future [7]. It has been estimated that with this improvement the electrical efficiency will be increased by 1.5% percentage points [56]. Specific investment costs may increase by 2% percentage point if advanced materials are used and the boilers are changed from BFB to CFB [56]. Also the electricity production cost could increase 3% with the modifications to needed to use advanced steam conditions [56]. The cost of electricity production in a steam cycle using wood chips (no flue gas condensing) is around 0.077 EUR/kWh and with flue gas condensing 0.071 EUR/kWh [57]. Around 2002, Wärtsilä started to commercialize its new boiler technology (Biograte). This configuration can produce between 1–5 MWe and up to 15 MWh [58] and several plants have been built in Europe.

7.1.2. Steam engines

The principle of operation of the steam engines is the same as for the conventional Rankine cycle where an engine is used instead of the turbine. Nowadays, the steam engine has been replaced by more economical applications such as steam turbine, internal combustion engines and electric motors. The main advantage of steam engines is that they can use the same biofuels as the conventional steam cycle. One of the main obstacles is that for a given pressure the steam engine cannot handle as high level of superheating

as a steam turbine can [59]. Technical limitations in the lubrication system also complicate the use of advanced steam conditions. Additionally, the engine is extremely noisy and requires constant maintenance.

7.1.3. Gas turbines

If natural gas or other high-quality fuel is available, the advantages of gas turbines compared with steam turbines include higher efficiencies, lower capital costs, faster startup times, lower manpower operating needs, higher availability, and smaller size [55,60]. The most important development trends for gas turbines are increased temperatures, increased pressure ratio, and the introduction of intercoolers and recuperators [60]. Gas turbines have high reliability. However, they have high noise levels, long overhaul periods and their output depends on the ambient conditions [61]. The steam produced in a heat recovery steam generator (HRSG) can be high quality steam needed for industrial purposes or to drive a steam turbine [55]. For small-scale gas turbines research is currently focused on the use of ceramic material in the hot parts of the gas turbine [56].

Fuel quality issues have hindered the utilization of biofuels in gas turbines. In principle biofuels can be used, although there are several considerations that should be taken into account. For the case of biofuels with a low LHV, a redesign of the fuel handling system is needed to allow for the relatively high mass flow. This problem does not arise with high-methane landfill gas. If a biomass gasifier is used, the raw biogas must be cleaned before the gas turbine to avoid erosion and corrosion in the turbine blades and a possible blockage of the filters and fuel injectors [62]. Attempts to directly fire gas turbines with solid biomass have revealed major difficulties [63].

Microturbines are typically smaller than their combined cycle counterparts and do not feature a steam bottoming cycle. Instead, heat recovery may be enhanced with gas turbine-side components like recuperators or intercooling [64]. Most commercially available microturbines consist of a generator, turbine and compressor mounted on a common shaft, and very high rotational speeds are often employed (e.g. 90,000 rpm [65]). Microturbines are characterized by automatic operation, good part-load performance, and low emissions [64]. Low vibration levels and modularity make the microturbine an interesting alternative for distributed power generation/CHP if the biofuel quality is sufficiently high.

7.1.4. Reciprocating internal combustion engines

Reciprocating internal combustion engines are very common in small-scale applications generating electricity and heat (through heat recovery from the exhaust gas, oil and cooling water). It is a robust technology, well-proven and reliable but requires frequent maintenance.

Otto engines are widely used in European countries for small-scale applications. This technology is well proven and is under continuous development for achieving higher efficiencies and improved environmental performance. When natural gas is used in small-scale applications, the investment and operational costs are significantly reduced. Otto engines are highly competitive for small-scale CHP plants below 2 MWe. They have a long lifetime, good part load operation and a short start-up time. Otto engines also exhibit high levels of low frequency noise and have high maintenance costs [61]. The higher investment cost does not motivate the implementation of engines in a micro-scale. In Sweden, CHP plants with less than 1 MWe output are mainly gas engines using biogas. Gas engines using biogas from waste, water treatment plants or biomass have been identified as potential niches for small-scale applications in Sweden. The cost of generating electricity with

methanol is 0.13 EUR/kWh, with biogas 0.11 EUR/kWh and with gasification of wood chips 0.069 EUR/kWh [57].

Diesel engines are also used in small-scale power production. Diesel engines have relatively low investment cost per kWe power output. The part load operation of Diesel engines is good and their start-up time is short. The new development and research on Diesel engines is mainly focused on emissions reduction via catalytic converters and other technology [56].

7.1.5. Stirling engines

Stirling engines theoretically employ the same cycle as the Carnot cycle, thus they have the potential for higher efficiencies as compared to the Rankine or Joule cycle [55]. Stirling engine technology has the interesting prospect of high efficiency, good performance at partial load, low emission level, low vibration and low noise level [55]. The working fluid in the Stirling engine can be hydrogen, helium or air. Since combustion occurs externally, Stirling engines can use any kind of fuel. In Sweden, the possibility to use Stirling engines fuelled with biogas and landfill gas is very promising; according to a Swedish study [66]. Also, two manufacturers located in Sweden suggest that Stirling engines can also use wood pellets as fuel. In the case that thermal gasification of biomass is used, it is possible to avoid corrosion and erosion in the engine and to control the combustion process more easily than in a directly fired engine [8]. Stirling engines are usually automated and are relative easy to maintain. From the micro-cogeneration point of view, Stirling engines have many advantages: the electricity production in Stirling engines is independent from the heat production, the engines are easy to control and they can be built as an interchangeable unit [61]. The power output is between 2 and 50 kWe and the electrical efficiency varies between 15 and 35% [67]. The cost of a Stirling engine is quite high today and it is around 3300–3900 EUR/kWe [68].

7.1.6. Fuel cells

Fuel cells have a high electrical efficiency even in small-scale applications and therefore they are recommended when power output is the primary goal. Fuel cells are one of the most promising novel technologies for distributed small-scale applications [69]. They can be automatically operated, they allow quick load changes, they have low maintenance needs and have a flexible power to heat ratio [61]. The main drawbacks of the fuel cells are high material and manufacturing costs, low density effect, fuel availability or the need to separate the hydrogen with a reformer, and high specific investment costs around 5000 EUR/kWe [68].

7.1.6.1. Phosphoric acid fuel cell. Phosphoric acid fuel cell (PAFC) has a working temperature of 150–220 °C [56]. It is the type of fuel cell that has been researched for the longest period [55]. The only suitable fuel is hydrogen, so other components such as CO have to be removed [66]. Natural gas has been used in general and some demonstration plants have also tested methanol [59].

7.1.6.2. Solid oxide fuel cell. Solid oxide fuel cell (SOFC) has a working temperature of 950–1000 °C that makes it attractive for cogeneration purposes [55]. For small-scale CHP plants, SOFC's have been envisioned for power output range between 5 and 10 kWe [70]. Pure hydrogen or a mixture of hydrogen and CO can be used as fuel in SOFCs [55]. It has been suggested that SOFCs can be combined with a gas turbine or a microturbine to increase the electrical efficiency up to 60% and the total efficiency up to 80% [56,71]. In January 2000, the preliminary testing of the SOFC coupled with a 50 kWe gas turbine was carried out giving a total power output of 250 kWe and successfully demonstrating the technical feasibility of this arrangement. The SOFC is a technology still under development. Research is needed for materials used in this fuel cell at high

temperatures and also possibilities to decrease the operating temperature and thus the manufacturing cost as cheaper material can be used [68].

7.1.6.3. Molten carbonate fuel cell. The molten carbonate fuel cell (MCFC) can be used in a combined cycle scheme where the heat from the fuel cell is used to produce steam in a conventional steam cycle [56]. The working temperature of a MCFC is usually 600–700 °C [55] which reduces the size of the catalyst for fuel reforming and also the cost [66]. Natural gas can be transformed directly to hydrogen via internal reforming in the fuel cell. However, more research is needed on high temperature materials and the possibility to use natural gas directly [66].

7.1.6.4. Polymer electrolyte fuel cell. The polymer electrolyte fuel cell (PEFC) has a low operational temperature (around 90 °C) so it is most suitable for electric power production alone. Like many other fuel cell types, PEFC's need highly pure hydrogen to operate. However, there is interest in Sweden for small-scale power generation applications [56].

7.2. Technologies under research and development

7.2.1. Organic Rankine cycle

The organic Rankine cycle (ORC) operates with the same principle as the conventional Rankine cycle but with an organic fluid (i.e. toluene, propanol, isobutane and CFC's) as a working media. ORC's are especially suitable for waste heat applications, since process streams at less than 500 °C can be utilized [69]. The possible heat sources include the exhaust from a Diesel engine, gas turbine, hot gases from kilns in ceramic industry, blast furnaces in the steel industry and geothermal energy [69]. The organic fluids are more expensive than water and losses of the fluid can represent significant costs [55]. The fluids (e.g. toluene) are also considered hazardous materials. Therefore, safety and materials-handling systems can increase ORC costs [55]. It has been estimated that the average availability of an ORC cycle is 80–90% with a lifetime of 20 years [55] and an electricity production cost of 0.0275 EUR/kWh [72].

In the past, biomass-based ORC plants have been successfully demonstrated in the range of 400–1500 kWe and are being commercialized [73]. In spite of all the issues mentioned above, there are several plants already operating in the world. At least 2 manufacturers are already implementing these plants in a wider scale.

7.2.2. Air bottoming cycle

The air bottoming cycle (ABC) is a type of combined cycle in which the heat of exhaust gases from a gas turbine is used as a heat source for another turbine [74]. The working fluid of the bottoming turbine is air. The ABC is considered as a competitive technology to steam cycles in medium and small-scale plants [74]. The ABC can increase the efficiency of a gas turbine by increasing the power output approximately 25% compared with a simple gas turbine. The advantage of the ABC cycle is that the working fluid of the bottoming cycle can also be used in other purposes, e.g. space heating or drying. The ABC cycle has the possibility to produce cooling, heating and electricity in a so-called trigeneration scheme (triABC). One of the drawbacks of the ABC is the cost of the plant. This can be improved by reducing the size of the plant using the high-speed technology applied to microturbines and it has been estimated that a cost of 0.023 EUR/kWh can be achieved [75].

7.2.3. Evaporative gas turbine

The evaporative gas turbine (EvGT) is sometimes also called humid air turbine (HAT) [56]. Its main feature is that water is added to the cycle before the combustion [69]. This plant has a gas turbine, recuperator, humidification tower, heat exchanger

and flue gas condenser [69]. The steam is produced by evaporating water droplets in the compressed hot air through the use of a humidifier [69]. About 75% of the water can be recovered using flue gas condensing. A pilot plant has been built at Lund Institute of Technology in Sweden [76] and features a 600 kWe natural gas fired gas turbine. The high efficiency of the EvGT makes it a competitive technology with Diesel engines and combined cycles in small and medium range [56]. Economic analyses show a 30% lower cost for electricity production with EvGT compared to a combined cycle, mostly due to the elimination of a steam turbine and condenser [60]. It is estimated that EvGT will be available for commercial heat and power production by 2010 [56]. In terms of environmental performance, the injection of steam before the combustion helps to regulate the peak flame temperature and therefore limits the production of NOx [56,69]. It is expected that the plant operation will cost 7 €/MWh [76].

7.2.4. Externally fired gas turbine

The externally fired gas turbine (EFGT) is a gas turbine in which the combustion chamber has been replaced with a heat exchanger. The combustion can take place in a large variety of boilers and the presence of a heat exchanger between the boiler and the turbine ensures the purity of the EFGT working fluid. The most suitable boiler for EFGT is the CFB boiler due to its fuel flexibility, high efficiency and low NOx emissions. From the environmental point of view, well-proven methods for emissions control can be used to improve the environmental performance of the plant. Because the working fluid in the EFGT is clean the risk of contamination of sensitive components is lower [77]. However, the temperature limitation of the heat exchanger is an important constraint for the efficiency that can be achieved. Thus, further development of the heat exchangers is still needed to increase the turbine inlet temperature. Research on metallic and ceramic materials for hot gas heat exchangers is ongoing worldwide [56]. The cost of electricity in an EFGT cycle is estimated to be 0.073–0.084 EUR/kWh [77].

In the range of micro-scale applications, externally fired micro-turbines can represent an interesting alternative in Sweden and Finland where the use of wood-derived fuels is common for CHP applications. Some efforts are currently done by a Swedish company in order to test and commercialize this technology [78] and one of the units is currently used in a research project at the Royal Institute of Technology.

7.2.5. Pulverized wood-fired gas turbine or solid-fired gas turbine and combustion engine

The most suitable internal combustion engine for using directly pulverized wood is the Diesel engine. However, there are problems

to find the wood powder with suitable properties and particle size [19]. The electrical efficiency for a direct fired motor is estimated between 35 and 40% [56].

7.2.6. Thermionic converters and thermophotovoltaics converter

Thermionic converters transform thermal energy directly into electricity. A thermionic converter consists of two metal electrodes placed in a vacuum chamber or in a chamber filled with Cesium gas. One of the electrodes supplies heat at higher temperature (1000–1500 °C) and the other rejects heat at lower temperature (500–800 °C). The thermionic converter does not have any moving parts and it can be used in a process where waste heat is the energy source. For example, a thermionic converter can be installed in a boiler and use 10% of the supplied energy to convert it to electricity without affecting the total efficiency [59]. In theory, if the thermionic converter is coupled to a conventional steam cycle the electrical efficiency can reach 44–46% [59]. Some advantages of the thermionic converter are the possibility to use different fuels, the possibility to connect several thermionic converters in parallel (i.e. similar to fuel cells), its low maintenance cost and long lifetime. However, the thermionic system is not yet well developed and tested [59].

Thermophotovoltaics (TPV) converters use photovoltaics cells to transform radiation energy from a source with lower temperature than the sun to electricity. This energy can come from biomass combustion or propane. The Solar Energy Research Center (SERC) in Dalarna, Sweden is looking at the possibility of using wood as a fuel for a TPV-system emphasizing the aspect of co-generation of heat and electricity [79].

7.3. Review of distributed generation technologies using biofuels

The most important parameters for each technology reviewed are listed in Table 8a.

8. Bioenergy policies

8.1. Environmental taxes and electricity certificates in Sweden

Since the 1950s the Swedish government has set a tax on energy and at the beginning of the 1990s established taxes on CO₂, sulfur and NOx, depending on different variables including the fuel type. Table 9 shows the energy and environmental taxes from January 1st 2010 [12] excluding the 25% value-added tax.

The energy tax is applied to most of the fuels independently of the energy content. However, biofuels are excluded of this tax [12].

Table 9
Energy and environmental taxes in Sweden [12] and the energy market 2010.

Fuel	Energy tax	CO ₂ tax	Sulfur tax	Total tax	Tax [EUR cents/kWh]
Gas oil [EUR/m ³] (<0.1% S)	88	335	0	423	4.24
Bunker oil [EUR/m ³] (0.4% S)	88	335	12	435	4.1
Coal [EUR/t] (0.5% S)	37	291	17	345	4.57
LPG [EUR/t]	17	352	0	369	2.89
Natural gas [EUR/1000 m ³]	28	250	0	278	2.53
Peat [EUR/t] 45% moist. 0.24% S	0	0	5.6	5.6	0.20
Unrefined tall oil [EUR/m ³]	423	0	0	423	4.31
Domestic waste [EUR/t fossil carbon ^a]	18	427		445	1.79
Biofuels [EUR/t]	0	0	0	0	0
Electricity use					
Northern Sweden [EUR cents/kWh]	2.06	–	–	2.06	2.06
Rest of Sweden [EUR cents/kWh]	3.11	–	–	3.11	3.11
Industrial operations [EUR cents/kWh]	0.06				0.06

^a The proportion of fossil carbon is assumed 12% of the weight of the refuse.

Table 10
Energy taxes in Finland in 2011 [90].

Fuel	Energy tax	CO ₂ tax	Security of supply fee	Total
Heavy fuel oil [EUR/t]	87.9	97.2	2.8	187.9
Hard coal [EUR/t]	54.54	72.37	1.18	128.09
Peat [EUR/MWh]	1.90	–	–	1.90
Natural gas [EUR/MWh]	3.00	5.94	0.084	9.024
Pine oil [EUR cents/kg]	0.1879			18.79
Electricity				
Tax class I [EUR cents/kWh]	1.69	–	0.013	1.703
Tax class II (industrial user) [EUR cents/kWh]	0.69	–	0.013	0.703

The CO₂ tax depends on the amount of carbon dioxide emitted by the fuels except biofuels (including waste) and peat [12]; it is also applied for heat production in boilers or CHP plants [69]. The sulfur tax was also introduced in 1991 but, biofuels do not have this tax [12]. In 1992, the NO_x tax was introduced and since 2008 a rate of 50 SEK/kg of NO_x emissions has been applied to power plants producing more than 25 GWh/y of electricity [12]. The tax is based on the NO_x emissions measured at the stack. However, if there are no measurements a value of 250 mg/MJ is assigned [69]. This tax is repaid to the operators based on their energy production, their NO_x emissions and the average emissions of the country [69].

Electricity taxes vary depending on the region (sparsely populated regions in the north are favored) [69]. Also, fuels used for electricity production are exempt of energy and CO₂ tax [12]. In the case of biofuels it is exempted of sulfur tax but subject to NO_x tax. For the case of heat production, thermal plants pay energy tax, CO₂ tax, sulfur tax and NO_x tax. Here, biofuels are exempt of energy, CO₂ and sulfur taxes (excluding peat). For CHP plants covered by the EU emissions trading scheme, fuels used for electricity production receive a discount on CO₂ tax which by January 2010 will mean that only 7% of the CO₂ tax will be levied.

In May 2003, electricity certificates were introduced in Sweden with the aim to foster the use of renewable energy for electricity production, namely from solar, wind, hydropower and biofuels [12]. The Swedish government has set the target of increasing by 17 TWh/y the production of electricity from renewable energies by 2016 (compared to the 2002 production) [12,84]. The basis of the system is that each producer receives one certificate for each MWh of electricity produced from renewable energy. Users are required to buy a certain amount of certificates based on a specific quota according with their electricity consumption. This quota is raised every year thus, favoring the increase in the production of green electricity. As a result of the certificate system, production of renewable electricity had net increase of 11.4% between 1900 and 2009 [12,84]. The price of the electricity certificate is determined by supply and demand. In 2009, the average price was 30 EUR/MWh [12]. With the electricity certificate system, electricity producers will have an extra income besides the selling of electricity that will help the production of electricity from renewable energy [12]. In this system of electricity certificates the subsidy for small scale CHP plants of less than 1500 kW (0.01 EUR/kWh) disappeared [85]. The investment support from the government which could represent up to 25% for biomass-based CHP plants has also been eliminated when the electricity certificates were introduced.

8.2. Energy tax in Finland

Finland has also been active in promoting the switch of fuels away from oil after the crisis in 1970s. This was done as a way to reduce dependence on petroleum products. Finland was the first country to introduce CO₂ tax in 1990 [86] but it took some time until the tax reached a point that favored biomass fuels, as discussed by Ericsson et al. [87]. A reform, when the energy tax was introduced, came into force in September 1st, 1998 after some

adjustments related to EU tax harmonization and the opening of the Nordic electricity market Nordpool [88]. The energy tax consists of three components: a basic tax on oil products, an additional tax for transport and heating fuels and a tax on electricity consumption for industrial users and other users. A security of supply fee was introduced for non-indigenous resources. Biofuels are exempted of the energy tax as well as electricity generation [89].

A new taxation reform came into force in January 2011 [90]. In this reform, an ascending tax on peat came into force. For natural gas tax adjustments will take place until 2015. The main difference with the old taxation system is that CO₂ tax is based on a life cycle approach to emissions [90]. Table 10 summarizes the different taxes.

Finland has also subsidized biomass plants in an effort to reduce oil consumption. During 1990s this subsidy was between 10 and 25% of the investment cost of the biomass plant [87]. The maximum available investment subsidy was 30% [87]. Furthermore, biomass plants receive a subsidy per MWh almost equal to the industrial electricity consumption tax. There have been proposals in favor of a fixed energy price for small-scale producers for a period of 15 years. The purpose of this fixed tariff is to compensate for the high costs of small-scale production [91].

9. Summary and future outlook

In terms of technology, the most commonly adopted technology for Swedish and Finnish CHP plants in the range from 2 MWe to 20 MWe is fluidized bed with steam turbine. In the size range from 1 MWe to 2 MWe there are also plants based on a biomass grate boiler. Under 1 MWe size there is one demonstration plant on bio-fuel gasification connected to a gas engine, and many plants using natural gas as a fuel in a gas engine. Natural gas has been used as fuel also in demonstrations based, e.g. on microturbine, fuel cells and evaporative gas turbine. In Sweden there has been also one demonstration project on Stirling engines, where wood pellets have been used as fuel. The main goal of these demonstration projects has been to increase the fuel conversion efficiency in the smallest size range of CHP applications and to make it possible to use biofuels with the new technologies currently under development.

According to the results of the technological assessment, it is possible to identify the most suitable technologies for each of the scales considered. For cogeneration applications in the 1–20 MWe range, the possible alternatives are the conventional Rankine cycle, gas turbine with HRSG, air bottoming cycle, internal combustion engines, SOFCs and MCFCs. For the conventional Rankine cycle, any kind of biofuel can be used although the most common are solid biofuels. The use of biofuels in gas turbines is possible with some modifications on the fuel handling system and the combustion chamber. At smaller scales (50–1000 kWe) microturbines, Stirling engines, fuel cells and internal combustion engines are the most promising technologies. However, the fuel availability represents an important factor in the use of particular technology. If the main fuel sources are solid biofuels, then Stirling engines could be the most suitable alternatives for cogeneration purposes. In the case

of liquid biofuels, internal combustion engines, microturbines and PEFC's can be used. For gaseous biofuels, it is possible to utilize any of the above mentioned alternatives. The outcome of continuing and future research and development efforts in biomass conversion technologies like gasification and others will also be influential in this context.

Regarding potential and future development of CHP in Finland, the immediate challenge is to increase the share of wood fuels in the district heating sector as well as the replacement of oil as fuel in CHP production. There is also potential to expand the use of distributed CHP systems. These two factors have substantial importance on the future increase of biomass-based CHP generation depending on the market conditions. Currently, the low electricity prices and higher investment cost do not favor the implementation of these systems. Also, it is very difficult to compete with large-scale plants due to the better performance in terms of emissions and economics. However, the possible installation of small-scale district heating networks can change this perspective. Furthermore, the replacement of small-scale district heating plants with CHP units certainly represents an interesting alternative. Another possible niche market are industrial users that would like to produce their own electricity, especially if the fuel is ready available. As was discussed previously, the potential of CHP plants using biofuel, natural gas and peat has been estimated between 610 and 3700 MWe and between 1040 and 5010 MWh for different operating conditions [40]. From this potential it has been calculated that between 74 and 91% would be in the size below 20 MWh.

On the other hand, Sweden is in a slightly different position. The opportunities to replace district heating plants with CHP are significant considering the electricity certificate system. In 2009, about 53 TWh of district heating was delivered and 9.8 TWh of electricity was produced at the same time [92]. Thus, there is a great potential to convert district heating units to CHP. It has been estimated that about 20 TWh of electricity can be delivered [16]. Additionally, Pålsson [93] has estimated that about 850 GWh are required in the south of Sweden and that 75% can be covered with small-scale CHP production, mainly for the wood industry, small district heating grids and boilers. In any case, most opportunities are currently in the renewable sector particularly in the biomass sector considering the current taxation system.

In both countries, there is a niche market for biomass plants such as the conversion of heating boilers to CHP plants and the replacement of fossil fuels from medium-scale CHP plants. The possible utilization of solid biomass fuels in CHP plants of less than 1 MWe still remains a technological challenge which undermines its applicability and wide commercialization in spite of being one of the most interesting niche markets.

Interest in the development of biomass-based CHP certainly extends beyond Sweden and Finland, and it is expected that new technologies will emerge as a result of various national and international efforts. Small-scale systems will most probably be a prominent element on the road towards a sustainable energy future.

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